PART I: SEPTEMBER 11, 2001

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Chapter 1
NEW YORK CITY'S WORLD TRADE CENTER

1.1 THE ORIGINATION

In 1960, American technology was on the rise, and internationalism was a prominent theme. It was in this technical and global political context and this year that the planning began for a World Trade Center (WTC) to be located in lower Manhattan. From its first conception during the 1939 World's Fair in New York, it now emerged under the powerful advocacy of the Chase Manhattan Bank's David Rockefeller. Here was a grand plan that would embody the concept of New York City as a center of world commerce and provide a home for numerous international trade companies.

The organization that would build the World Trade Center was The Port of New York Authority, later to be renamed as The Port Authority of New York and New Jersey (The Port Authority, PANYNJ). Created in 1921, under a clause in the United States Constitution, to run the multijurisdictional commercial zones in the region, The Port Authority built and operated facilities on the banks of the Port of New York's waterways, the bridges to cross them, and the major metropolitan airports. It had the authority to obtain land by eminent domain and to raise funds for its projects. Now, under the leadership of its Executive Director, Austin Tobin, the concept for the World Trade Center grew from the grand plan of David Rockefeller to the grandeur of the world's largest office complex.

To fulfill all the functional, aesthetic, and economic desires for this concept, innovative architecture was needed. In 1962, the firm of Minoru Yamasaki & Associates was hired to perform the architectural design, which was first unveiled in 1964. The team also involved Emory Roth & Sons, P.C., as the architect of record.[1] The structural engineering was by Worthington, Skilling, Helle and Christiansen. (Some time after completion of the construction, Skilling, Helle, Christiansen, and Robertson, and then Leslie E. Robertson Associates (LERA) assumed that role.) Jaros, Baum & Bolles were hired as the mechanical engineers, and Joseph R. Loring & Associates were the electrical engineers. Tishman Construction Corporation was the general contractor.

In 1966, the formal groundbreaking for the towers took place. Construction began in 1968, with the first occupancy in 1970. These dates establish the historical context for the building codes and the state of practice under which the complex was designed and constructed. This will be discussed further in Part II.

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[1] The functions of these entities are as follows. In New York City, a permit, issued by the building commissioner, is required to construct, alter, repair, demolish or remove any building. The architect who signs and generally files the plans (as part of the process for securing the permit) and takes the lead role of a project is the architect-of-record. Specific subsets of plans may be signed by the structural, electrical, and mechanical engineers, representing the separate disciplines involved in those subsets. The filed plans are reviewed and approved for compliance with the building code requirements by the building commissioner before issuance of the permit.

The City of New York had no jurisdiction. However, The Port Authority required that all the WTC tower plans be submitted for their review and approval for code compliance and other architectural requirements. The responsibility of technical correctness rested with the architect of record and the engineers of record.

The expected tenancy by companies involved in international trade did not materialize as conceived, so the State of New York, the City of New York, and The Port Authority became the principal WTC tenants in the 1970s. As the years passed, however, the prestige of the address grew, and the requirement that occupants be involved in international trade was relaxed. At the end of the twentieth century, the World Trade Center was nearly fully occupied by a diverse mixture of large and small businesses and federal, state, and city government organizations.

1.2 THE WORLD TRADE CENTER COMPLEX

1.2.1 The Site

By 2001, the WTC complex had become an integral part of Manhattan. It was composed of seven buildings (here referred to as WTC 1 through WTC 7) on a site toward the southwest tip of Manhattan Island (Figures 1–1 and 1–2). Whether viewed from close up, from the Statue of Liberty across the Upper Bay or from an aircraft descending to LaGuardia Airport, the towers were a sight to behold. The two towers, WTC 1 (North Tower) and WTC 2 (South Tower), were each 110 stories high, dwarfing the other skyscrapers in lower Manhattan and seemingly extending to all Manhattan the definition of "tall" previously set by midtown's Empire State Building. WTC 3, a Marriott Hotel, was 22 stories tall, WTC 4 (South Plaza Building) and WTC 5 (North Plaza Building) were each 9-story office buildings, and WTC 6 (U.S. Customs House) was an 8-story office building. These six buildings were built around a 5-acre Plaza named in honor of Austin Tobin. WTC 7 was a 47-story office building on Port Authority land across Vesey Street on the north side of the Plaza complex. Built over the ConEd substation serving the WTC complex, it was completed in 1987 and was operated by Silverstein Properties, Inc.

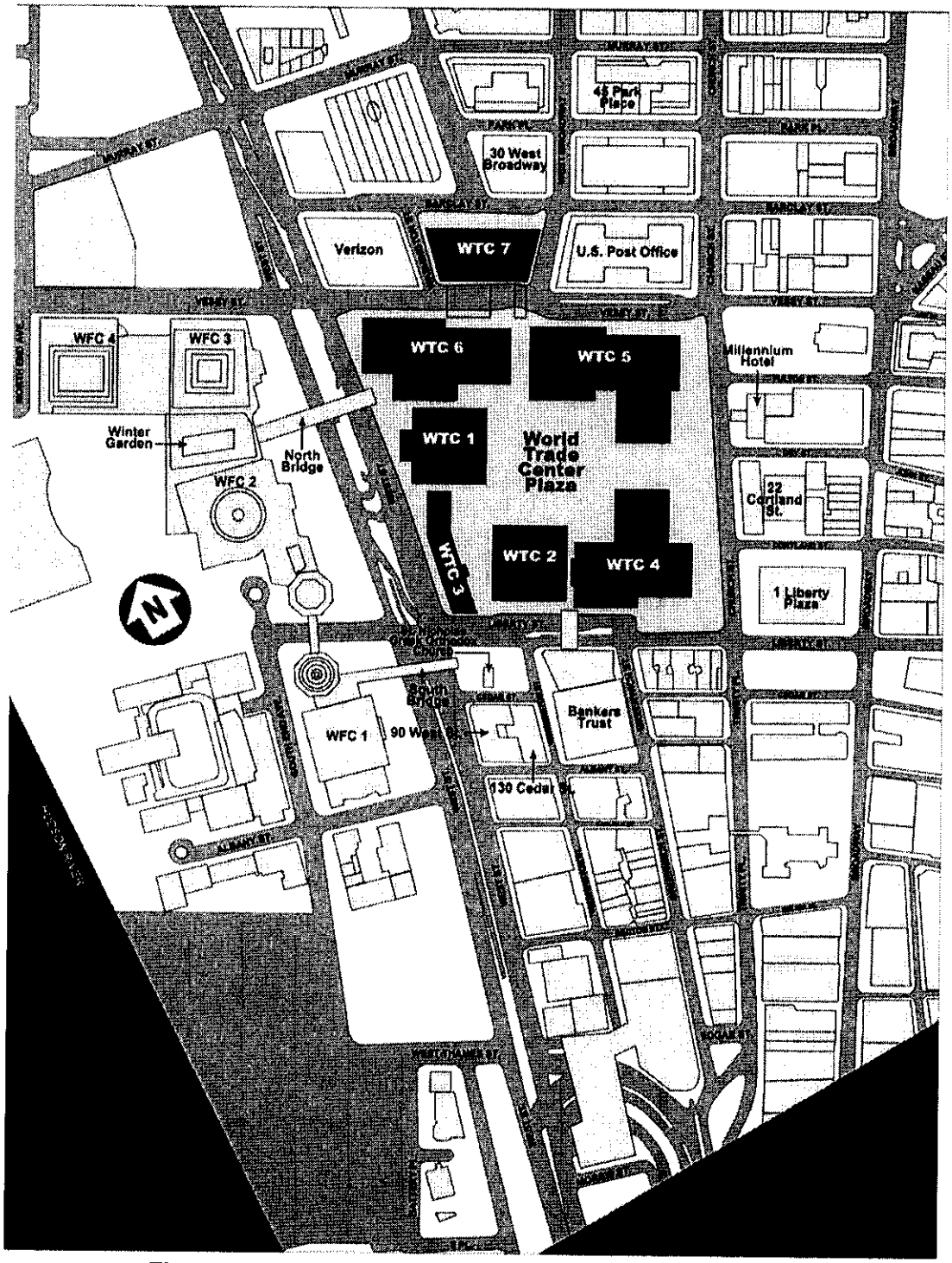
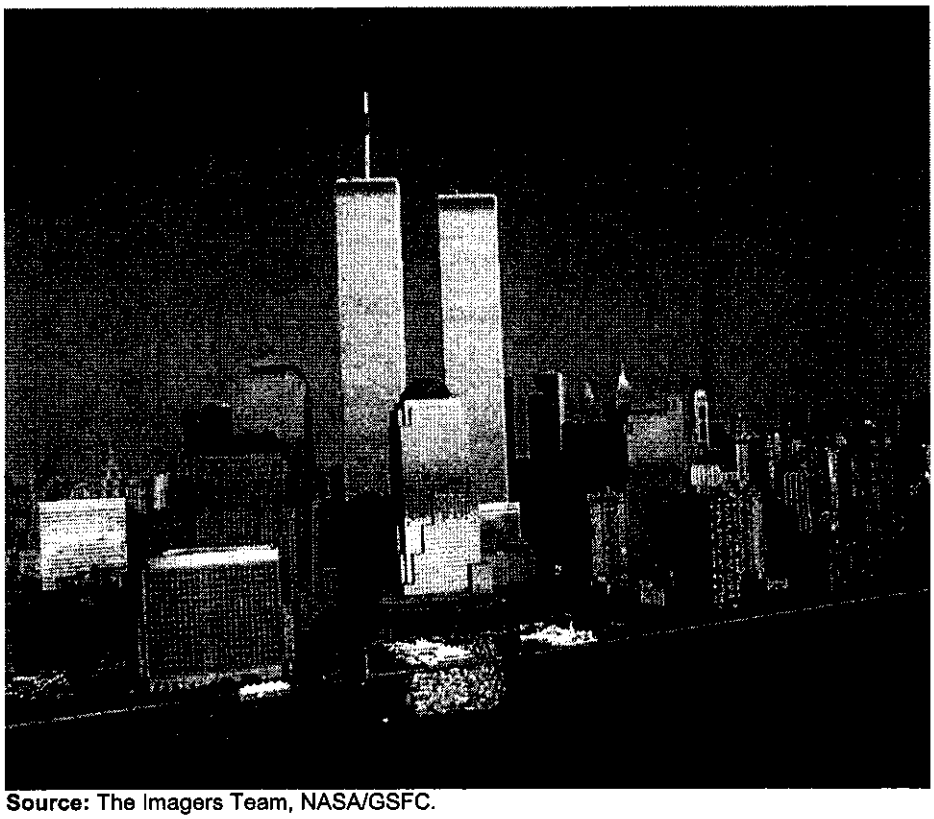


Figure 1–1. The World Trade Center in Lower Manhattan.



Source: The Imagers Team, NASA/GSFC.

Figure 1–2. Lower Manhattan and the World Trade Center towers.

Below the 11 western acres of the site, underneath a large portion of the Plaza and WTC 1, WTC 2, WTC 3, and WTC 6, was a 6-story underground structure. The structure was surrounded by a wall that extended from ground level down 70 ft to bedrock. Holding back the waters of the Hudson River, this wall had enabled rapid excavation for the foundation and continued to keep groundwater from flooding the underground levels.

Commuter trains brought tens of thousands of workers and visitors to Manhattan from Brooklyn and New Jersey into a new underground station below the plaza. A series of escalators and elevators took the WTC employees directly to an underground shopping mall and to the Concourse Level of the towers.

1.2.2 The Towers

The Buildings

The focus of the complex was on the two towers, each taller than any other building in the world at that time. The roof of WTC 1 was 1,368 ft above the Concourse Level, 6 ft taller than WTC 2, and supported a 360 ft tall antenna mast for television and radio transmission. The footprint of each tower was a square, about 210 ft on a side (approximately an acre), with the corners of the tower beveled 9 ft 9 in. Internally, each floor was a square, about 206 ft on a side.[2]

The superb vistas from the top of such buildings virtually demanded public space from which to view them, and The Port Authority responded. The 107th floor of WTC 1 housed a gourmet restaurant and bar with views of the Hudson River and New Jersey to the west, the skyscrapers of midtown Manhattan to the north, the East River and Queens and Brooklyn to the east, the Statue of Liberty to the southwest, and the Atlantic Ocean to the south. Similar views could be seen from observation decks on the 107th floor and the roof of WTC 2.

Table 1–1 shows the use of the floors, which was similar but not identical in the two towers.

Table 1–1. Use of floors in the WTC towers.

Floor(s)	WTC 1	WTC 2
Roof	Antenna space and window washing equipment	Outdoor observation deck and window washing equipment
110	Television studios	Mechanical equipment
108, 109	Mechanical equipment	Mechanical equipment
107	Windows on the World restaurant	Indoor observation deck
106	Catering	Tenant space
79 through 105	Tenant space	Tenant space
78	Skylobby, tenant space	Skylobby, tenant space
77	Tenant space	Tenant space
75, 76	Mechanical equipment	Mechanical equipment
45 through 74	Tenant space	Tenant space
44	Skylobby, cafeteria, tenant space	Skylobby, tenant space
43	Port Authority space	Tenant space
41, 42	Mechanical equipment	Mechanical equipment
9 through 40	Tenant space	Tenant space
7, 8	Mechanical floors	Mechanical floors
Concourse through 6	6-story lobby	6-story lobby

[2] Extensive details regarding all aspects of this report are found in the supporting Investigation reports listed in Appendix B. A subject index of those reports appears as Appendix C to this report. Those reports, in turn, cite the numerous documents made available to the Investigation Team. To maintain continuity, citations of the source documents are not included in this report. They are found in the supporting Investigation reports.

The Port Authority had managed the operation of the two towers since their opening three decades earlier. Silverstein Properties acquired a 99-year lease on the towers in July 2001.

The Structures

Each of the tenant floors of the towers was intended to offer a large expanse of workspace, virtually uninterrupted by columns or walls. This called for an innovative structural design, lightweight to minimize the total mass of 110 stories, yet strong enough to support the huge building with all its furnishings and people. Structural engineers refer to the building weight as the *dead load*; the people and furnishings are called the *live load*. Collectively, these are referred to as *gravity loads*. The buildings would also need to resist *lateral loads* and excessive swaying, principally from the hurricane force winds that periodically strike the eastern seaboard of the United States. An additional load, stated by The Port Authority to have been considered in the design of the towers, was the impact of a Boeing 707, the largest commercial airliner when the towers were designed, hitting the building at its full speed of 600 mph.

In 1945, a B-25 aircraft had become lost in the fog and struck the 78th and 79th floors of the Empire State Building. The building withstood the impact and ensuing fire and was ready for reoccupancy the following week.

Skilling and his team rose to the challenge of providing the required load capacity within Yamasaki's design concept. They incorporated an innovative framed-tube concept for the structural system. The columns supporting the building were located both along the external faces and within the core. The core also contained the elevators, stairwells, and utility shafts. The dense array of columns along the building perimeter was to resist the lateral load due to hurricane-force winds, while also sharing the gravity loads about equally with the core columns. The floor system was to provide stiffness and stability to the framed-tube system in addition to supporting the floor loads. Extensive and detailed studies were conducted in wind tunnels, instead of relying on specific, prescriptive building code requirements, to estimate the wind loads used in the design of these buildings.[3] This approach took advantage of the allowance by most state and local building codes for alternative designs and construction if evidence were presented that ensured equivalent performance.

A grade of steel is characterized by its yield strength, expressed in ksi, or thousands of pounds per square inch. This is the force per unit area at which the steel begins to undergo a permanent deformation. Different steel strengths, or grades, are manufactured by varying the chemistry and processing of the alloy. Higher strength steel is used when the design calls for more strength per weight of the steel column or beam.

There were four major structural subsystems in the towers, referred to as the exterior wall, the core, the floor system, and the hat truss. The first, the exterior structural subsystem, was a vertical square tube that consisted of 236 narrow columns, 59 on each face from the 10th floor to the 107th floor (Figure 1–3). There were also columns on alternate stories at each of the beveled corners, but these carried none of the gravity loads. (There were fewer, wider-spaced columns below the 7th floor to accommodate doorways.) Each column was fabricated by welding four steel plates to form a tall box, nominally 14 in. on a side. The space between the steel columns was 26 in., with a narrower,

[3] The studies showed that each tower affected the wind loads on the other. This effect was not accounted for in the prescriptive wind load requirements found in building regulations.

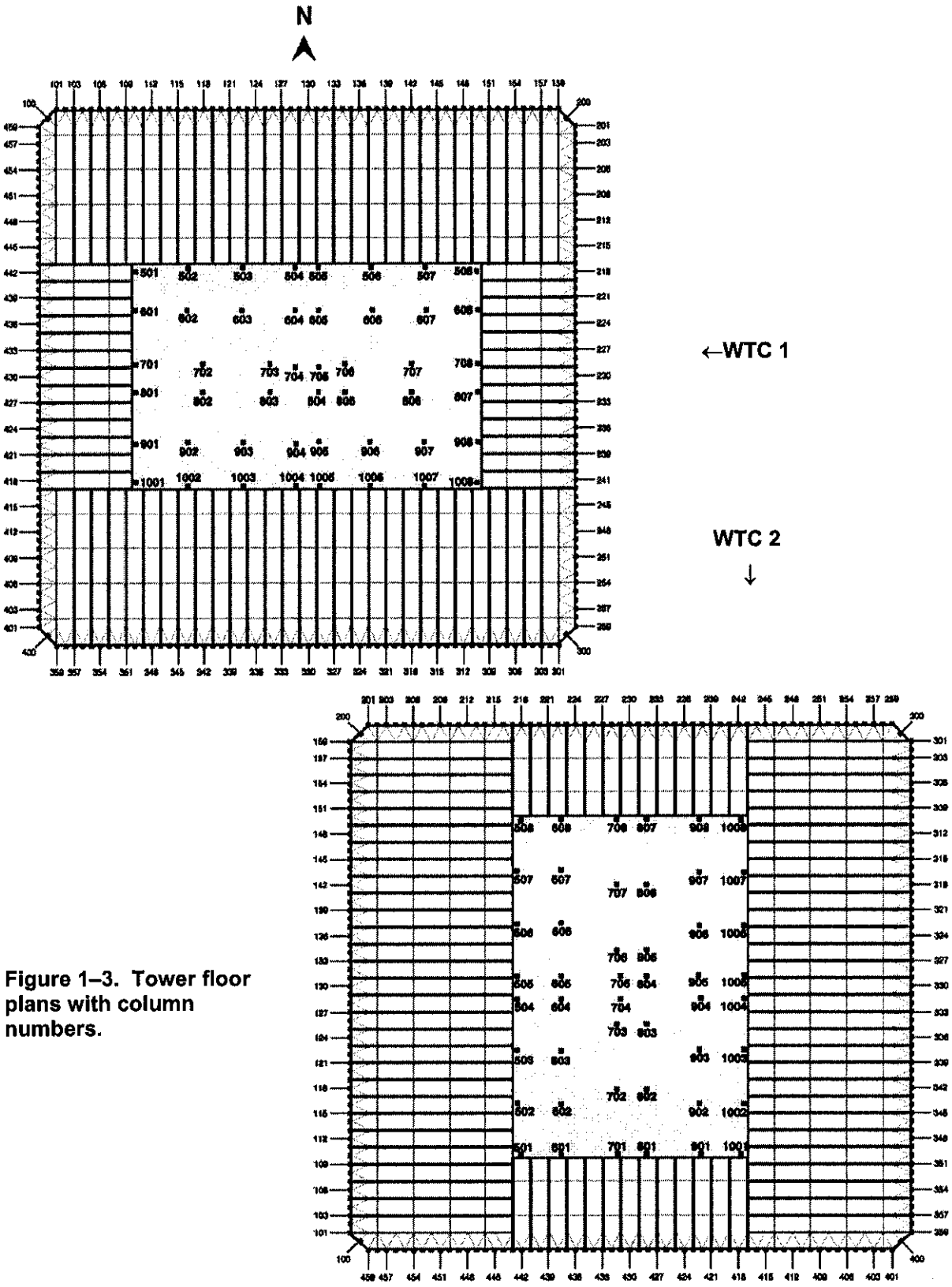
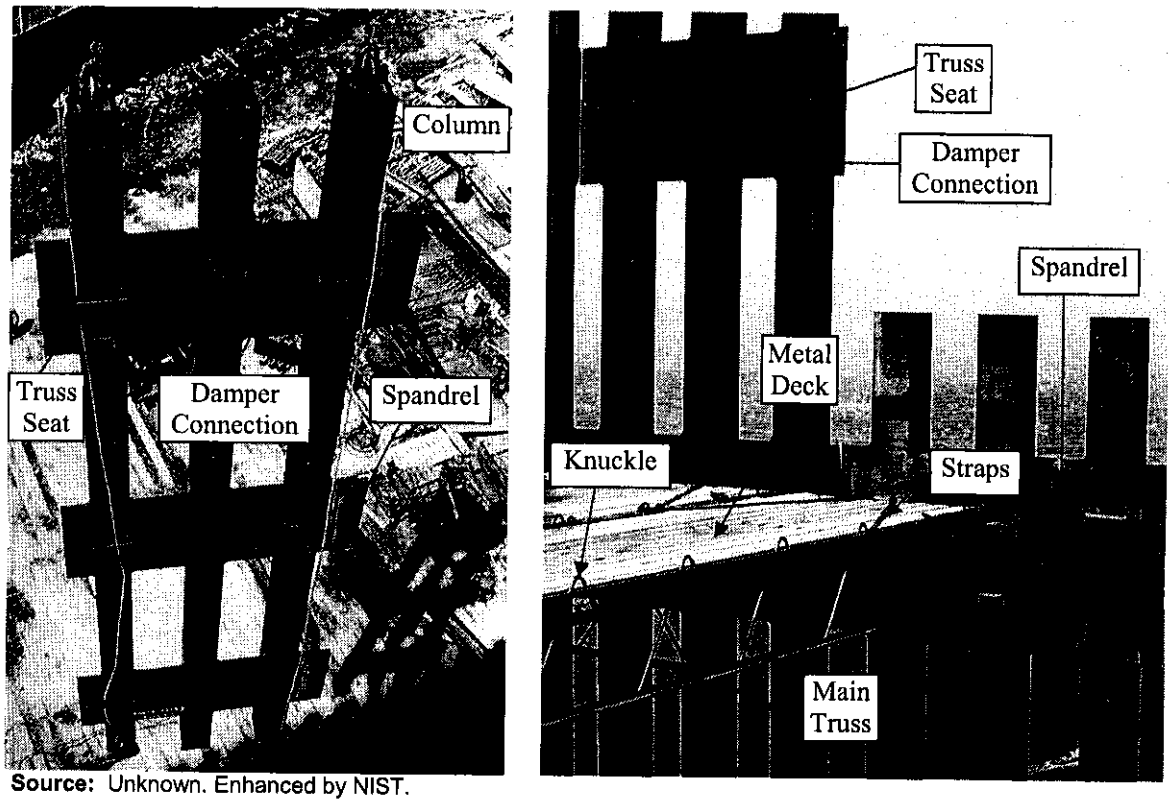


Figure 1–3. Tower floor plans with column numbers.

framed plate glass window in each gap. Adjacent columns were connected at each floor by steel spandrel plates, 52 in. high. The upper parts of the buildings had less wind load and building mass to support. Thus, on higher floors, the thickness of the steel plates making up the columns decreased, becoming as thin as ¼ in. near the top. There were 10 grades of steel used for the columns and spandrels, with yield strengths ranging from 36 ksi to 100 ksi. The grade of steel used in each location was dictated by the calculated stresses due to the gravity and wind loads.

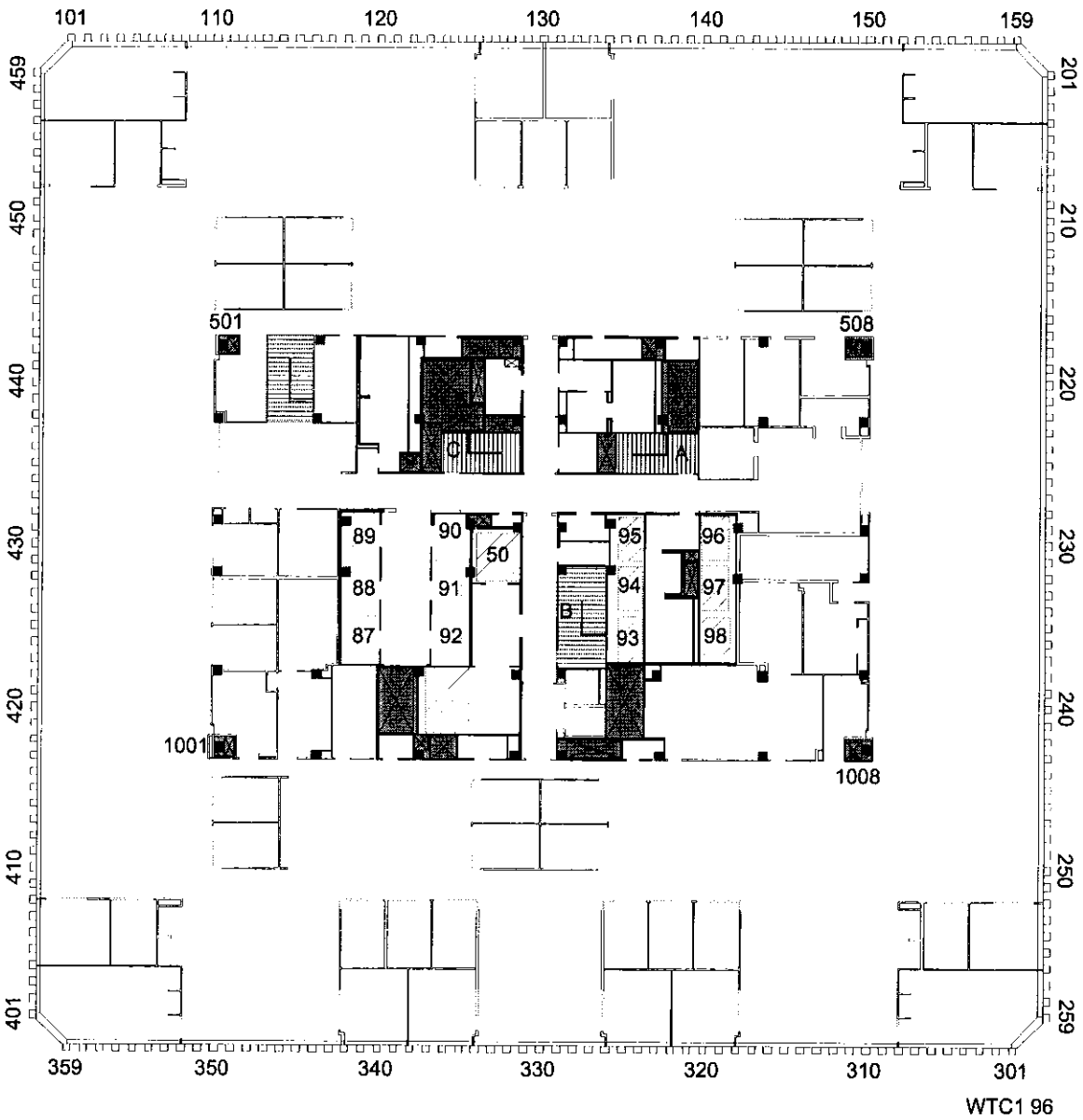
All the exterior columns and spandrels were prefabricated into welded panels, three stories tall and three columns wide. The panels, each numbered to identify its location in the tower, were then bolted to adjacent units to form the walls (Figure 1–4). The use of identically shaped prefabricated elements was itself an innovation that enabled rapid construction. The high degree of modularization and prefabrication used in the construction of these buildings and the identification, tracking, and logistics necessary to ensure that each piece was positioned correctly was unprecedented.



Source: Unknown. Enhanced by NIST.

Figure 1–4. Perimeter column/spandrel assembly and floor structure.

A second structural subsystem was located in a central service area, or core (Figure 1–5), approximately 135 ft by 87 ft, that extended virtually the full height of the building. The long axis of the core in WTC 1 was oriented in the east-west direction, while the long axis of the core in WTC 2 was oriented in the north-south direction (Figure 1–3). The 47 columns in this rectangular space were fabricated using primarily 36 ksi and 42 ksi steels and also decreased in size at the higher stories. The four massive corner columns bore nearly one-fifth of the total gravity load on the core columns. The core columns were interconnected by a grid of conventional steel beams to support the core floors.



Note: Column numbers are shown around the perimeter. The four corner core columns (501, 508, 1001, and 1008) are marked for orientation. Stairwells A, B, and C are shown in red stripes. The fourth red-striped area is the tenant's convenience stairwell that connected the 95th through 97th floors in WTC 1; it was not considered part of the egress system. The remaining numbers denote specific elevators. Much of the rest of the floor was open space suited for offices, conference rooms, or office cubicles. The arrangement and size of the core varied among the different floors.

Figure 1–5. Plan of the 96th floor of WTC 1 showing the core and tenant spaces.

The third major structural subsystem was the floors in the tenant spaces. These floors supported their own weight, along with live loads, provided lateral stability to the exterior walls, and distributed wind loads among the exterior walls. The floor construction was an innovation for a tall building. As shown in Figure 1–6, each tenant floor consisted of 4 in. thick, lightweight cast-in-place concrete on a fluted steel deck, but that is where "ordinary" ended. Supporting the slab was a grid of lightweight steel bar trusses. The top bends (or "knuckles") of the main truss webs extended 3 in. above the top chord and were embedded into the concrete floor slab. This concrete and steel assembly thus functioned as a composite unit, that is, the concrete slab acted integrally with the steel trusses to carry floor loads. The primary truss pairs were either 60 ft or 35 ft long and were spaced at 6 ft 8 in. There were perpendicular bridging trusses every 13 ft 4 in. The floor trusses and fluted metal deck were prefabricated in panels that were typically 20 ft wide and that were hoisted into position in a fashion similar to the exterior wall panels.

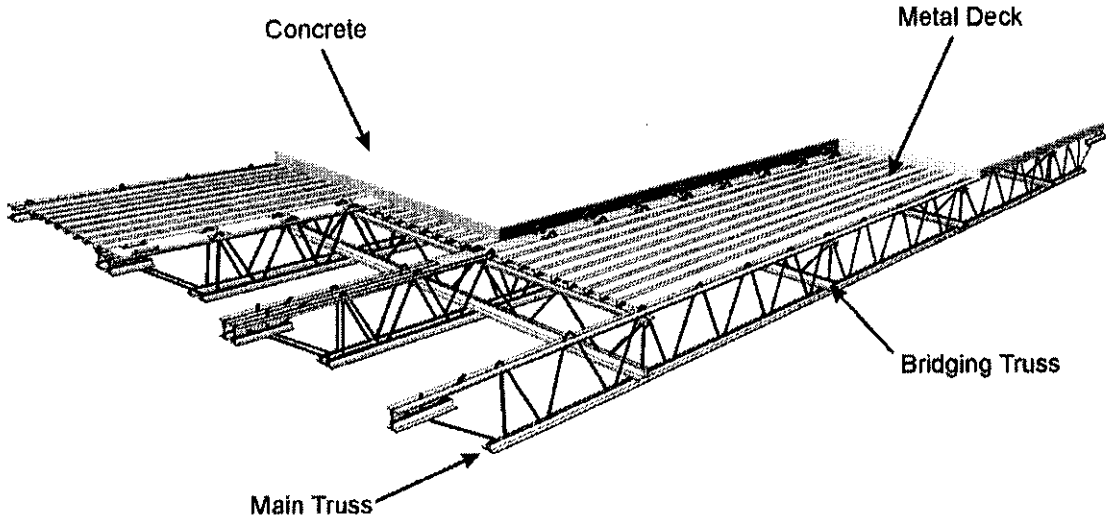


Figure 1–6. Schematic of composite floor truss system.

The bottom chords were connected to the spandrel plates by devices that were called viscoelastic dampers. Experiments on motion perception, conducted with human subjects, had shown a high potential for occupant discomfort when the building swayed in a strong wind. When the tower was buffeted by strong winds, these dampers absorbed energy, reducing the sway and the vibration expected from a building that tall. The use of such vibration damping devices in buildings was an innovation at that time.

The fourth major structural subsystem was located from the 107th floor to the roof of each tower. It was a set of steel braces, collectively referred to as the "hat truss" (Figure 1–7). Its primary purpose had been to support a tall antenna atop each tower, although only WTC 1 had one installed. The hat truss provided additional connections among the core columns and between the core and perimeter columns, providing additional means for load redistribution.

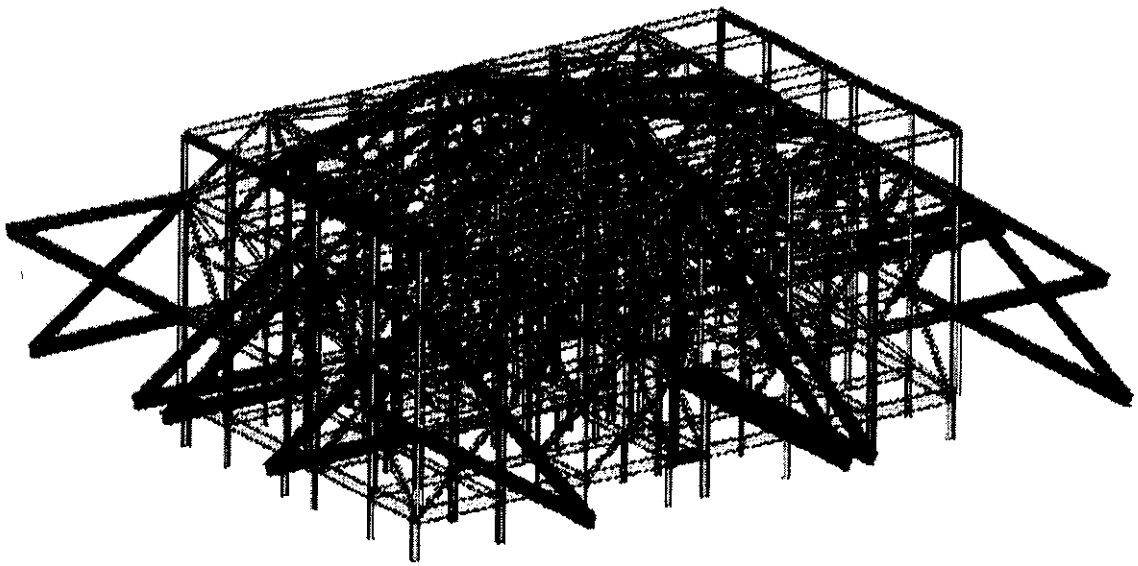


Figure 1–7. Schematic of a hat truss.

Fire Resistance

High-rise buildings in the United States are designed to meet requirements intended, among other objectives, to enable the building to suffer a sizable fire and still remain standing. The requirements are expressed in terms of fire resistance ratings, given in units of time.

The fire resistance of a column, wall, or floor design is rated by subjecting the assembly to standard heating conditions. A sample section of a wall to be tested is installed as one face of a furnace; a floor becomes the top of the furnace. Beams are normally rated as a part of the floor test. Floor systems are always tested while carrying their full design load. Walls are similarly loaded if they are intended to be load bearing, but are not loaded if the only load they are intended to support is their own weight. In the United States, columns are required to be loaded during the test, however, an alternative is often used, whereby the columns is not loaded and the temperature of the steel is used as a limiting criterion.

It is widely recognized in the building profession that fire resistance ratings, although expressed in hours, do not mean that the structure will sustain its performance for that length of time in a real fire. Actual fire performance may be greater or less than that achieved in the test furnace, depending on the severity of the actual fire exposure. Rather, these are taken as relative ratings, e.g., a wall rated at 2 hours will block the spread of a fire longer than a wall rated at 1 hour.

Fire Protection Systems

Bare structural steel components, when exposed to a large and sustained fire, can heat rapidly to the point where their ability to support their load is compromised. Thus, insulation is usually employed to encapsulate the steel and thus delay the heating of the steel. In the WTC towers, a major fraction of the core columns were enclosed or protected on several sides by sheets of gypsum wallboard. The trusses, perimeter columns, spandrels, and one or more surfaces of the core columns were coated with one of

three different sprayed fire-resistive material (SFRM). In this report, these materials are collectively referred to as "insulation."[4] The thickness of the wallboard or the SFRM was selected to provide an intended level of thermal protection. Figure 1–8 shows the appearance of a floor truss with sprayed insulation.

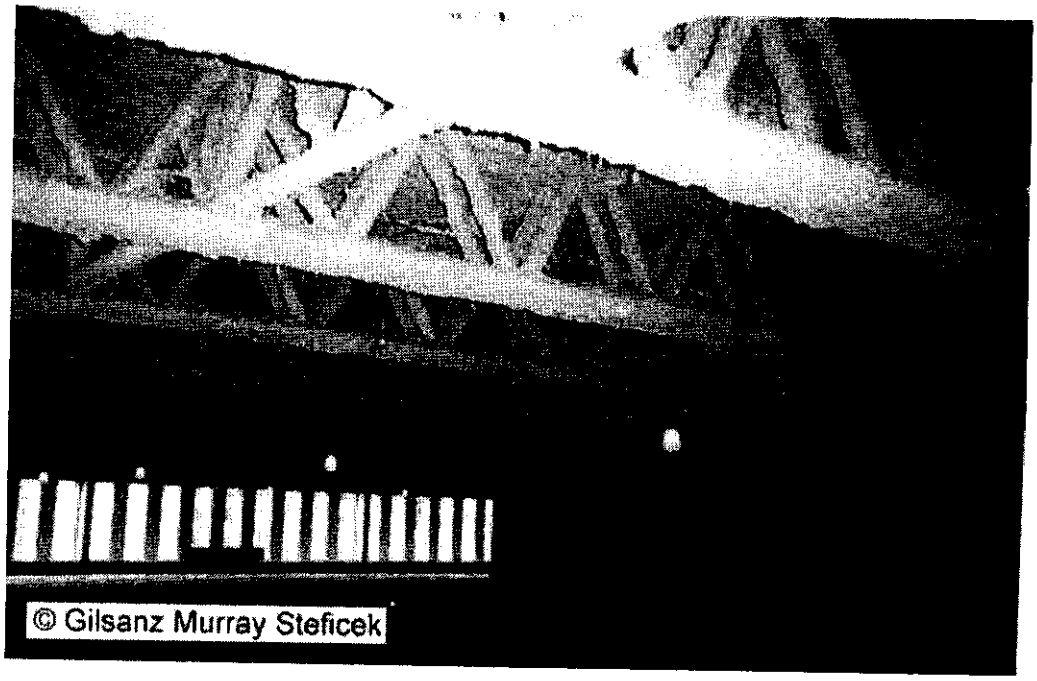


Figure 1–8. Photograph of insulated WTC trusses.

Further protection of the building against a fire was provided in part by internal, nonstructural, fire-rated walls. These floor-slab-to-floor-slab partitions, called demising walls, separated the tenant spaces from each other and from the core area. Their function was to keep a fire from spreading long enough for the fire to be extinguished. In a 1975 fire in WTC 1, these walls significantly confined the fire.

There were three types of nonstructural walls in the towers. The stairwells and elevator shafts were surrounded by 2 in. thick, tongue-and-groove, cast gypsum panels, covered with two or three sheets of 5/8 in. gypsum board. The demising walls were made of two sheets of 5/8 in. thick gypsum wallboard on each side of steel studs. These are often regarded as providing a 2 hour fire separation. Walls in the interior of the tenant spaces generally extended from the floor slab to the bottom of the drop ceiling and were made of single sheets of 5/8 in. gypsum wallboard over steel studs. These walls were not fire-rated. For some conference rooms and other spaces where sound barriers were desired, the walls extended to bottom of the floor slab above, in which case they were regarded as providing a 1 hour fire separation.

In addition to these methods of passive fire protection, there were components that would be activated in the event of a fire. Automatic fire sprinklers had been installed in all of the office spaces. NIST

[4] The materials used to insulate structural steel are sometimes colloquially referred to as "fireproofing," referring to the intent of the material, rather than the property it imparts. Since an important facet of this Investigation was the determination of the sufficiency of the insulation in protecting the steel from the heat of the fires, this report does not pre-judge the quality of the material by using the colloquial term.

calculations showed that the installed automatic sprinkler system was capable of delivering the minimum required water flow for control of office fires up to 4,500 ft^2. This was a small fraction of the 40,000 ft^2 size floors in the towers. In addition, in the stairwells, there were standpipes (for firefighters to connect their hoses) that were supplied with water by gravity feed from 5,000 gal tanks and by large fire pumps. A multifunction fire alarm system was intended to alert staff at the Fire Command Station within the building and provide voice and strobe alerts throughout. When turned on after the building had been cleared of people, a smoke purge system was intended to purge the hot, opaque fire gases from the building.

However, buildings were not (and still are not) required by the building codes or designed to withstand the impact of a fuel-laden jetliner. Although the impact of a Boeing 707 was stated by the Port Authority to have been considered in the original design of the towers, only one three-page document, in a format typically used for talking points was found that addressed the issue. This document stated that such a collision would result in only local damage and could not cause collapse or substantial damage to the building. NIST was unable to locate any evidence to indicate consideration of the extent of impact-induced structural damage or the size of a fire that could be created by thousands of gallons of jet fuel.

The Workplace

At the beginning of the workday, many of the roughly 40,000 people who worked in the towers and visited to conduct business or to tour emerged from trains in the massive subterranean station. They would take escalators and elevators to a one-story shopping mall, then pass through revolving doors to enter a spacious, 6-story-high lobby on the Concourse Level. There, they would cross paths with those who arrived on foot or by bus or cab.

Getting tens of thousands of people from the Concourse to their offices was no small task. This was accomplished by a combination of express and local elevators located within each of the building cores (Figure 1–9) that was novel at the time of construction.

- People traveling to floors 9 through 40 entered a bank of 24 local elevators at the Concourse Level. These were divided into four groups, with each stopping at a different set of eight or nine floors (9 through 16, 17 through 24, 25 through 31, and 32 through 40).
- Those going to floors 44 through 74 took one of eight express elevators to the 44th floor skylobby before transferring to one of 24 local elevators. These 24 were stacked on top of the lower bank of 24, providing additional transport without increasing the floor space occupied by the elevators.
- Those going to floors 78 through 107 took one of 11 express elevators from the Concourse Level to the 78th floor skylobby before transferring to one of 24 local elevators. These were also stacked on the lower banks of 24 local elevators.

While providing the desired high rate of people movement, this three-tier system used roughly 25 percent less of the building footprint than the conventional systems in which all elevators would have run from the Concourse to the top of the building, resulting in a building core that took up as much as one-half of the floor area. In addition, there was even more rentable space to be gained. At the top of each elevator bank, the machinery to lift the cabs occupied one additional floor. From the next floor up to the bottom of

the next bank, there was no need for an elevator shaft. The concrete floor was extended into this space, providing additional rentable floor area.

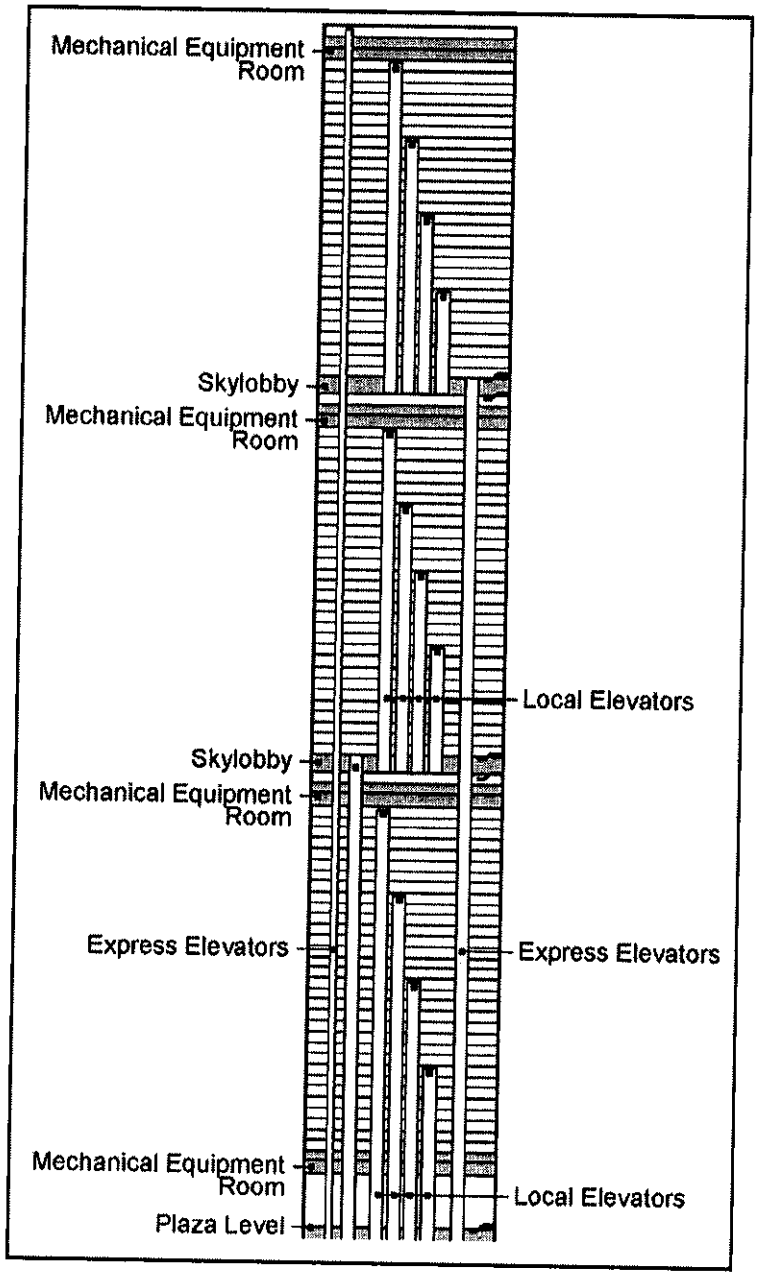


Figure 1–9. Schematic of the three-tier elevator system.

There were two additional express elevators to the Windows on the World restaurant (and related conference rooms and banquet facilities) in WTC 1 and to the observation deck in WTC 2. There were also five local elevators: three that brought people from the subterranean levels to the lobby, one that ran between floors 106 and 110, and one that ran between floors 43 and 44 (in WTC 1), serving the cafeteria

from the skylobby. There were also eight freight elevators, one of which served all floors. All elevators had been upgraded to incorporate firefighter emergency operation requirements.

Also within the core were three sets of stairs that extended nearly the full height of the tower (Figure 1–10). However, the stairwell at an upper floor did not continuously descend to the lobby, but rather to horizontal corridors in the vicinity of the mechanical floors. These enclosed corridors ranged in length from about 10 ft to about 100 ft. (As a result of these and the tiered elevator system, the core arrangements varied substantially from floor to floor.) After traversing each of these, the pedestrians would resume their descent, eventually reaching the tower lobby, from which they could exit the building. The advantages of moving stairwell locations included reclaiming core space for occupant use above terminated elevator shafts and overcoming obstructions posed by equipment installed on mechanical floors.

Following the February 26, 1993, bombing of WTC 1 and in light of the 4 hours needed to evacuate the building, several improvements had been made to the stairwells: battery operated emergency lighting, photoluminescent floor strips indicating the path to be followed, and explicit signs on each doorway to indicate where it led.

Upon exiting the elevators or stairs, the interior view was typical of high-rise buildings. Surrounding the rectangular core corridor was a mixture of walls, entry doors to firms, and glass-front reception areas. Above was a drop ceiling.

Many of the floors were occupied by a single tenant. Some of these tenants occupied multiple floors. By 2001, most of these companies had moved in after the installation of automatic sprinklers, which had allowed the absence of internal partitions. These companies largely took advantage of Yamasaki's design concept of a vast space that was nearly free of obstructions. The open arrangement often included as many as 200 or more individual modular workstations or office cubicles, generally clustered in groups of six or eight (Figure 1–11). Trading floors had arrays of tables with multiple computer screens (e.g., Figure 1–12, of a trading floor in WTC 4). Some of these floors had a few executive offices in the corners and along the perimeter. Many also had walled conference rooms. It was common for the tenants occupying multiple floors to create openings in the floor slabs and install convenience stairs between their floors.

Some floors were subdivided to accommodate as many as 20 firms. Some of the smaller firms occupied space in the core area in the spaces over the elevator shafts.

With thousands of workers and visitors in the buildings, there needed to be food service. The Port Authority maintained a cafeteria on the 43rd floor of WTC 1. In addition, a number of the companies maintained kitchen areas on their floors, where catered food was brought in daily, making it unnecessary for their staff to leave the building for lunch. There was a public cafeteria on the 44th floor of WTC 1. The visiting public could eat at Windows on the World at the top of WTC 1, at several restaurants on the observation deck of WTC 2, or in the many eateries on the Concourse Level. There were hundreds of restrooms, in both the tenant and the core spaces.

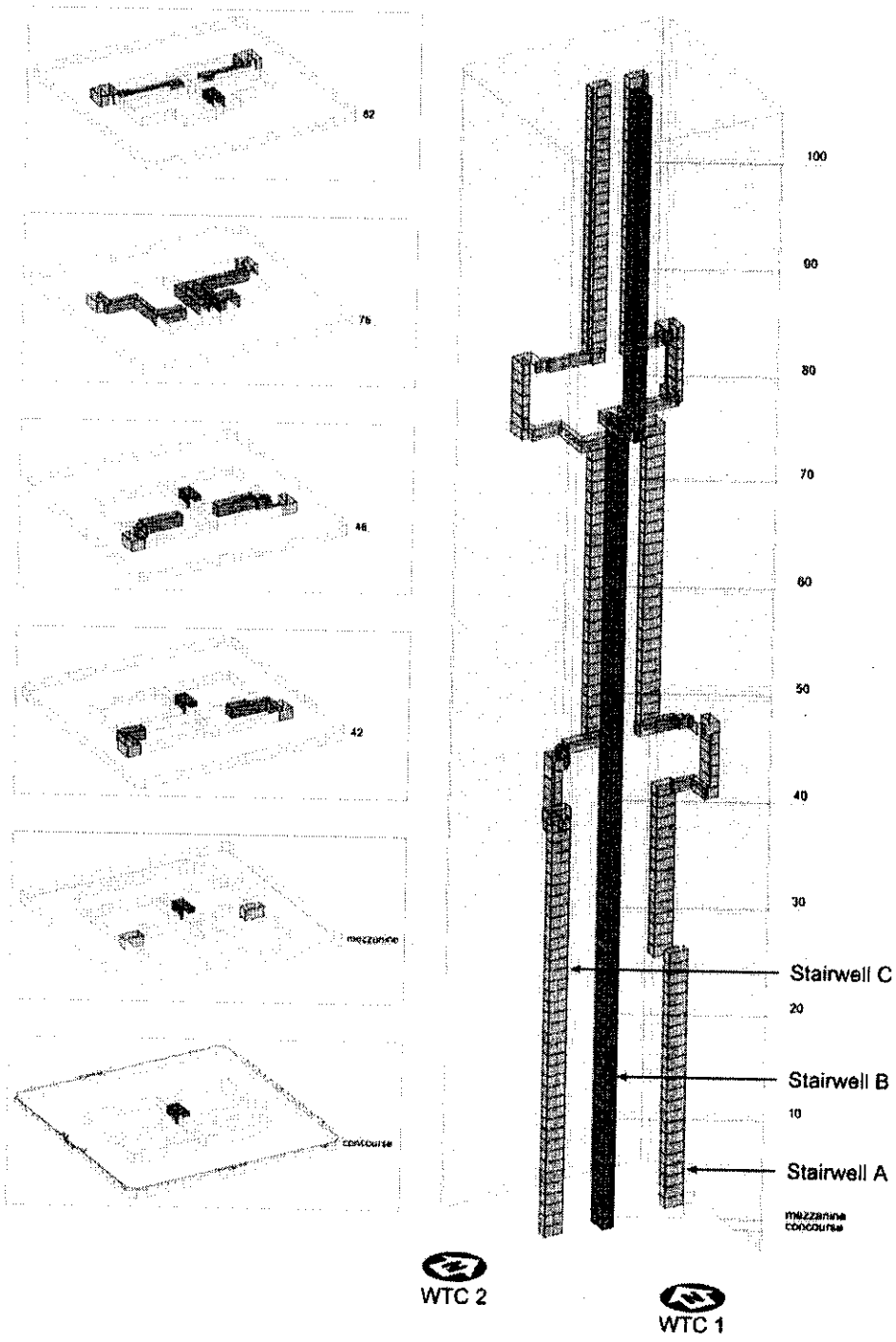


Figure 1–10. Orientation of the three stairwells.

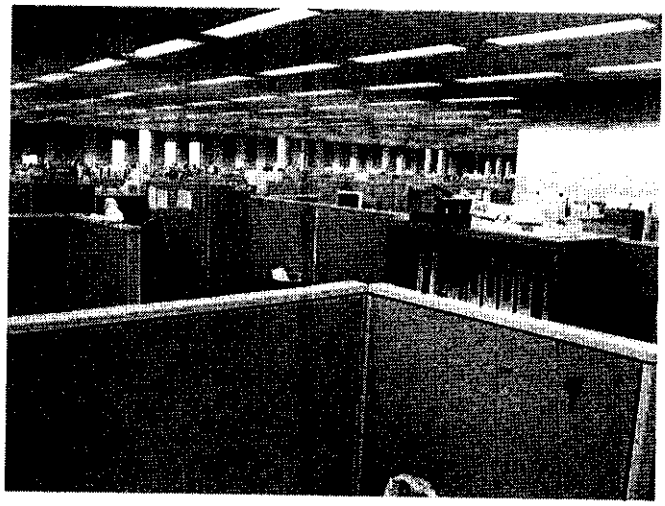


Figure 1–11. Views of typical WTC office floors.

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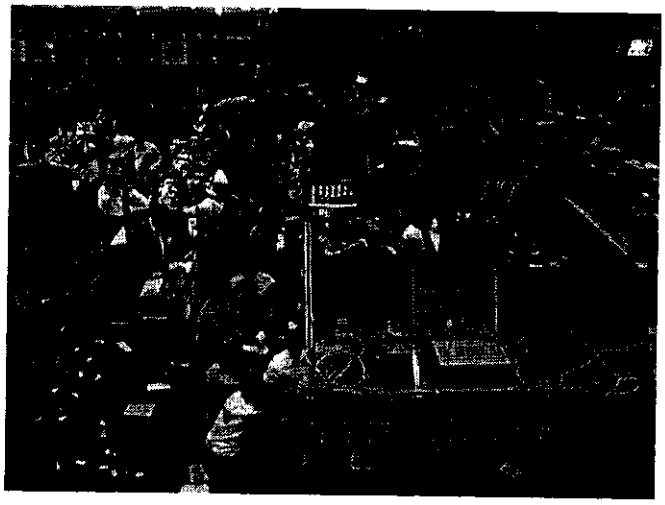

Figure 1–12. A WTC trading floor.

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Chapter 2
THE ACCOUNT OF WORLD TRADE CENTER 1

2.1 8:46:30 A.M. EDT

On the morning of Tuesday, September 11, 2001, a lot of people were going to be late for work in New York City, which for many started at 9:00 a.m. or later. It was the first day of school for many local children, and it also was a primary election day in New York. The weather was clear and comfortable with little wind to speak of, so some took time to do early morning errands. As a result, only about 8,900 of the typical 20,000 people were in World Trade Center (WTC) 1 shortly before 9:00 a.m.

At 8:46:30 a.m. EDT, five hijackers flew American Airlines Flight 11 (AA 11) with 11 crew and 76 passengers into the north face of WTC 1 (Figure 2–1).

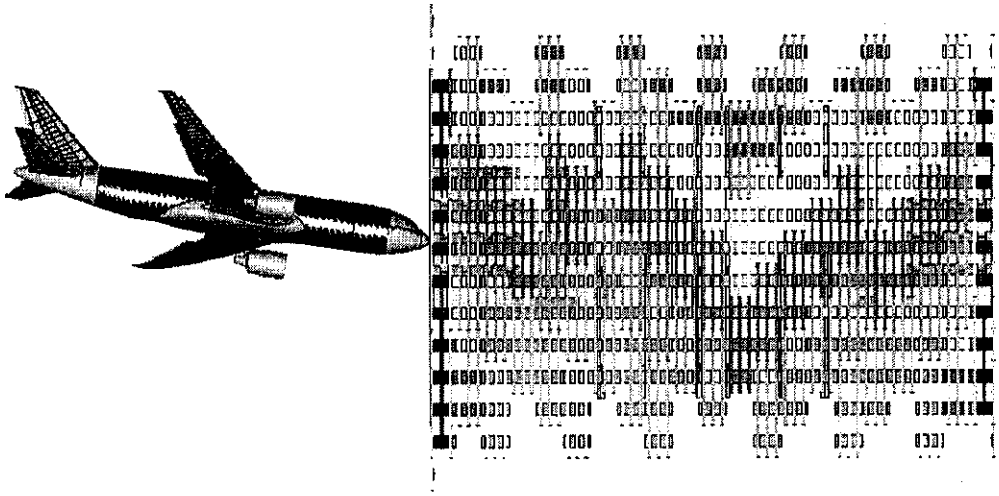


Figure 2–1. Simulated impact of American Airlines Flight 11 with WTC 1.

What follows is the result of an extensive, state-of-the-art reconstruction of the events that accompanied and followed the aircraft impact. Numerous facts and data were obtained, then combined with validated computer modeling to produce an account that is believed to be close to what actually occurred. However, the reader should keep in mind that the building and the records kept within it were destroyed, and the remains of the towers were disposed of before congressional action and funding was available for this Investigation to begin. As a result, there are some facts that could not be discerned, and thus there are uncertainties in this accounting. Nonetheless, the National Institute of Standards and Technology (NIST) was able to gather sufficient evidence and documentation to conduct a full investigation upon which to reach firm findings and recommendations. The reconstruction effort, the uncertainties, the assumptions made, and the testing of these assumptions are documented in Part II of this report.

2.2 THE AIRCRAFT

The Boeing 767-200ER was a twin-engine, wide-body aircraft, 159 ft 2 in. long, with a wingspan of 156 ft 1 in. Empty, it weighed 183,500 lb. It could carry 181 passengers in its three-class seating configuration and 23,980 gal (158,200 lb) of jet fuel as it covered its maximum cruising range of 6,600 miles. The maximum total weight the plane could carry was specified at 395,000 lb; the typical cruising speed was 530 mph.

The 767-200ER aircraft had two fuel tanks that extended through most of the interior of the wings and a center tank between the wings in the bottom of the fuselage. A full fuel load would have filled all three tanks.

On that day, AA Flight 11 was much lighter. Bound from Boston for Los Angeles, some 3,000 miles away, it carried only about half the full load of jet fuel. When it hit the north tower, it likely contained about 10,000 gal (66,000 lb), evenly distributed between the right and left wing tanks. Because of the tight maneuvers as the plane approached the tower, the baffles in both tanks had directed the fuel toward the inboard side of each wing. The passenger cabin was more than half empty. The cargo bay, carrying less than a full load of luggage, contained 5 tons of luggage, mail, electronic equipment, and food. The total weight of the aircraft was estimated to be 283,600 lb.

2.3 THE IMMEDIATE DAMAGE

The aircraft flew almost straight toward the north tower, banked approximately 25 degrees to the left (i.e., the right wing elevated relative to the left wing) and descended at an angle of about 10 degrees at impact. Moving at about 440 mph, the nose hit the exterior of the tower at the 96th floor. The aircraft cut a gash that was over half the width of the building and extended from the 93rd floor to the 99th floor (Figures 2–2 and 2–3). All but the lowest of these floors were occupied by Marsh & McLennan, a worldwide insurance company, which also occupied the 100th floor. Marsh & McLennan shared the 93rd floor with Fred Alger Management, an investment portfolio management company.

There was relatively little impact damage to the 93rd floor, hit only by the outboard 10 ft of the left wing. Containing no jet fuel, the wing tip was shredded by the perimeter columns. The light debris did minimal damage to the columns or to the thermal insulation on the trusses of the composite floor system supporting the 94th floor.[5] The trusses supporting the 94th floor were impacted by flying debris on the 93rd floor.

The 94th floor was more severely damaged. The midsection of the left wing, laden with jet fuel, and the left engine cut through the building façade, severing 17 of the perimeter columns and heavily damaging four more. The pieces of the aircraft continued inward, severing and heavily damaging core columns. The insulation applied to the floor trusses above and the columns was scraped off by shrapnel-like aircraft debris and building wall fragments over a wedge almost 100 ft wide at the north face of the tower and 50 ft wide at the south end of the building core.

[5] The reader should bear in mind that the described damage to the building exterior was derived from eyewitness and photographic evidence. The described damage to the aircraft and the building interior was deemed most likely from the computer simulations and analysis carried out under the Investigation.

Figure 2–2. Aircraft entry hole on the north side of WTC 1, photographed 30 s after impact.

The aircraft did the most damage to the 95th and 96th floors. The fuel-heavy inner left wing hit the 95th floor slab, breaking it over the full 60 ft depth of tenant space and another 20 ft into the building core. The fuselage was centered on the 96th floor slab and filled the 95th and 96th floors top to bottom. The severity of the impact was clear. A wheel from the left wing landing gear flew through multiple partitions, through the core of the building, and became embedded in one of the exterior column panels on the south side of the tower. The impact severed the bolts connecting the panel to its neighbors, and the panel and tire landed on Cedar Street, some 700 ft to the south. A second wheel landed 700 ft further south. Within the two floors, 15 to 18 perimeter columns and five to six core columns were severed, and an additional one to three core columns were heavily damaged. A 40 ft width of the 96th floor slab was broken 80 ft into the building. The insulation was knocked off nearly all the core columns and over a 40 ft width of floor trusses from the south end of the core to the south face of the tower.

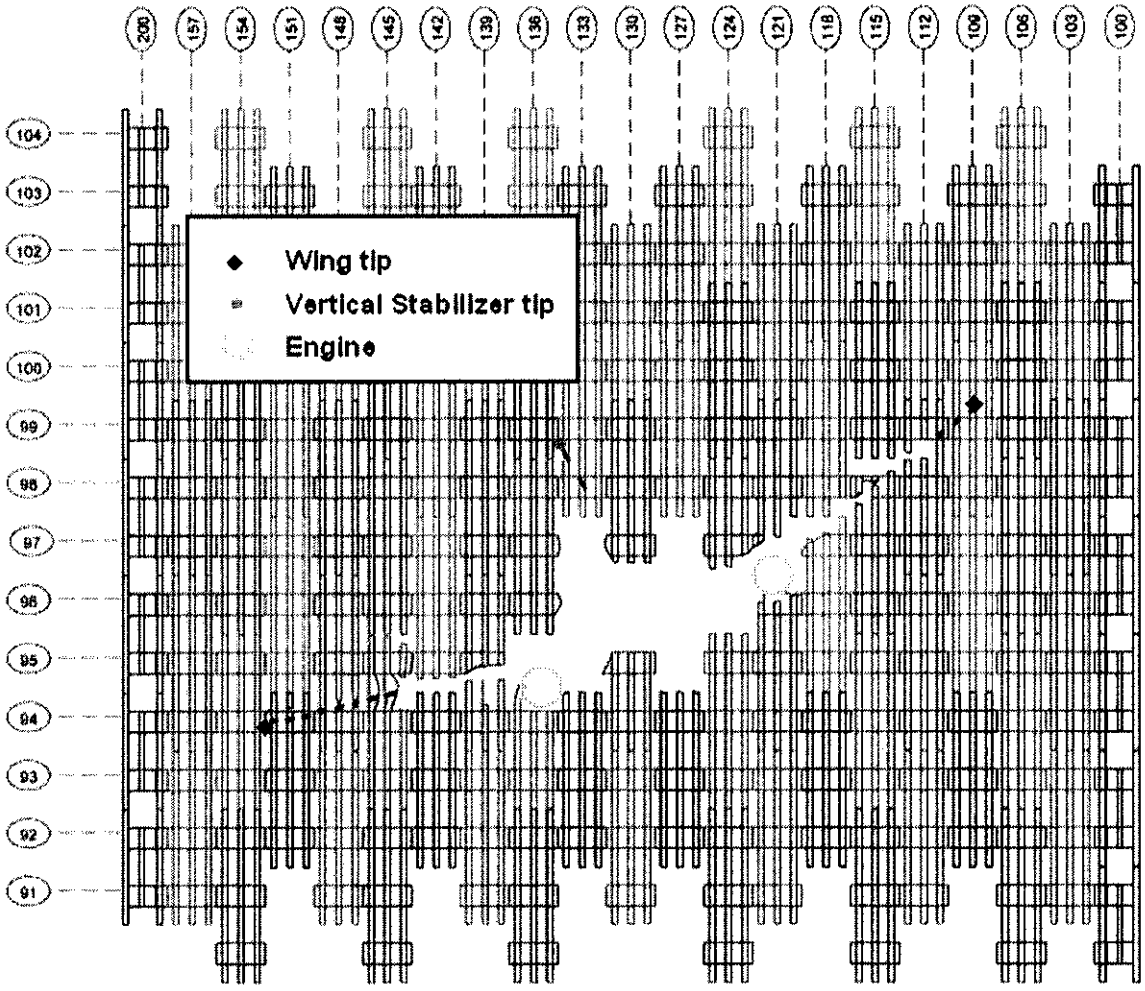


Figure 2–3. South face damage of WTC 1 with key aircraft component locations marked.

The right wing of the aircraft was fragmented by the perimeter columns on the 97th floor. In the process, 12 of those columns were severed. The debris cut a path through the west and center array of trusses and core columns, stripping the insulation over a 90 ft wide path. The insulation was stripped from a 50 ft wide path on the south side of the floor space.

On the 98th and 99th floors, the outboard 30 ft of the starboard wing was sliced by the perimeter columns, of which five were severed. The debris cut a shallow path through the west and center array of trusses, damaging the insulation up to the north wall of the building core.

This devastation took 0.7 s. The structural and insulation damage was considerable (Figure 2–4) and was estimated to be:

- 35 exterior columns severed, 2 heavily damaged.
- 6 core columns severed, 3 heavily damaged.

- 43 of 47 core columns stripped of insulation on one or more floors.
- Insulation stripped from trusses covering 60,000 ft^2 of floor area.

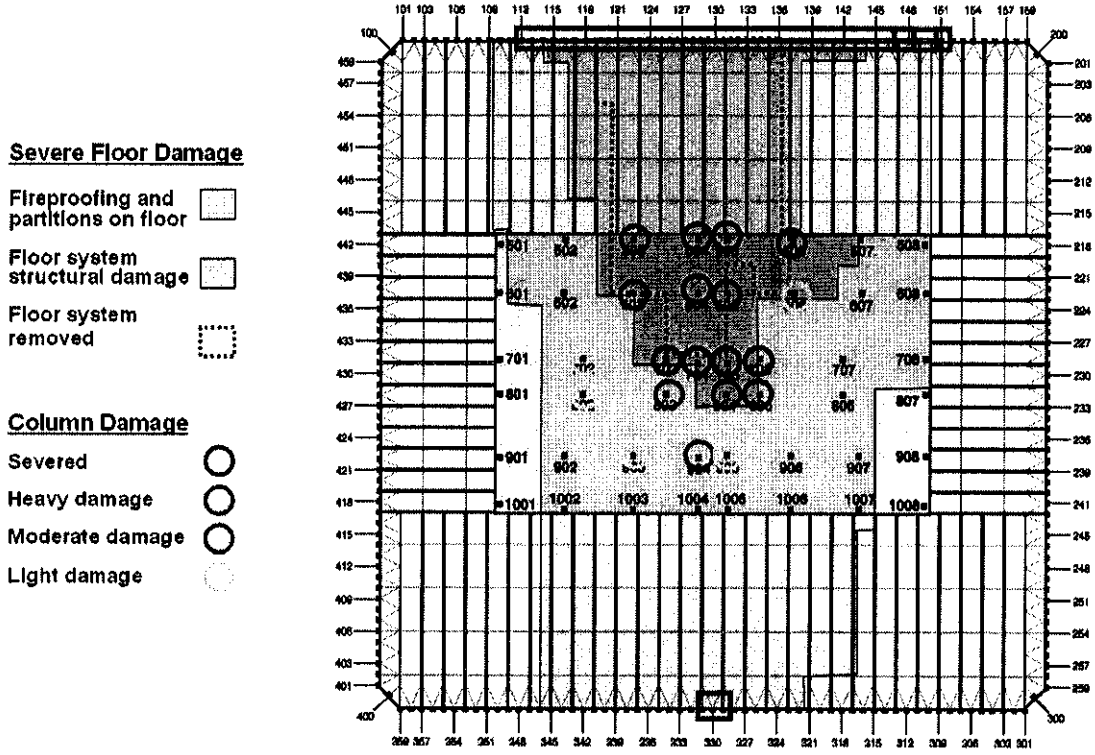


Figure 2–4. Simulation of cumulative aircraft impact damage to floors 93 through 98 in WTC 1.

Even with all this damage, the building still stood. The acceleration from the impact had been so severe that people even on lower floors were knocked down and furniture was thrown about. Some survivors reported fallen ceiling tiles throughout the building, all the way down to the Concourse Level. The pipes that fed the automatic fire sprinkler system were severed. At least 166 windows were broken. Damage to interior walls was reported from the Lobby to the 92nd floors. However, the building was designed with reserve capacity: it could support significantly more load than the weight of the structure and its people and contents. The building redistributed the load from the severed perimeter columns, mainly to their neighboring columns. The undamaged core columns assumed the remaining load, as well as the load from their damaged neighbors. WTC 1 still stood, and would have continued to do so, if not for the fires that followed.

NIST could not determine how many occupants were in the path of the aircraft as it entered the tower. Those in the direct collision path were almost certainly killed instantly. Many more would have lost their lives from the burst of heat from the burning jet fuel. Fatal injuries were reported on floors as low as the Concourse Level, where a fireball swept through the lobby.

In the impact region was further damage that would cost the lives of all the 1,355 people from the 92nd floor to the 110th floor. The crash and flying debris had collapsed the walls of all three stairwells and interrupted all elevator service to the upper 60 floors. All opportunity for escape had been eliminated.

2.4 THE JET FUEL

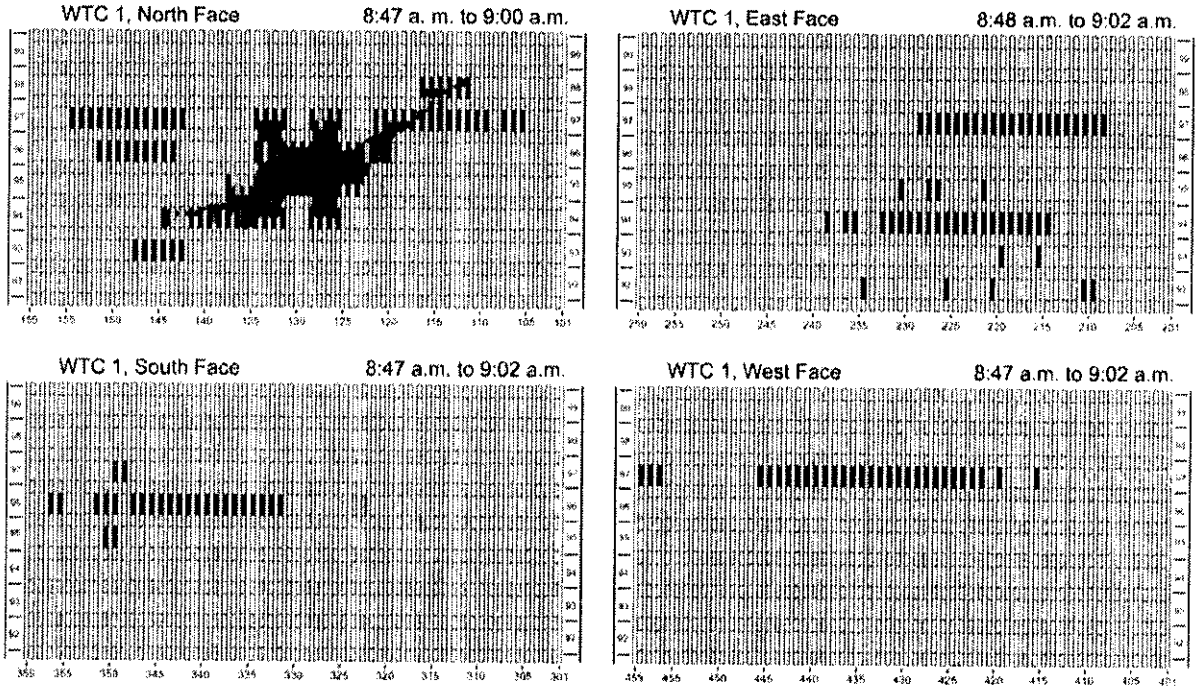
To the wings of the 767-200ER, the perimeter columns acted like knife blades, slashing the aluminum fuel tanks and atomizing much of the 10,000 gal of jet fuel liquid into a spray of fuel droplets. Atomized jet fuel is highly flammable (similar to kerosene), so both the hot debris and the numerous pieces of electrical and electronic gear in the offices were more than sufficient as ignition sources. A surge of combusting fuel rapidly filled the floors, mixing with dust from the pulverized walls and floor slabs. The pressure created by the heated gases forced the ignited mist out the entrance gash and blown-out windows on the east and south sides of the tower. The resulting fireballs could be seen for miles, precipitating many 9-1-1 calls.

Less than 15 percent of the jet fuel burned in the spray cloud inside the building. A roughly comparable amount was consumed in the fireballs outside the building. Thus, well over half of the jet fuel remained in the building, unburned in the initial fires. Some splashed onto the office furnishings and combustibles from the aircraft that lodged on the impacted floors, there to ignite (immediately or later) the fires that would continue to burn for the remaining life of the building. Some of the burning fuel shot up and down the elevator shafts, blowing out doors and walls on other floors all the way down to the basement. Flash fires in the lobby blew out many of the plate glass windows. Fortunately, there were not enough combustibles near the elevators for major fires to start on the lower floors.

2.5 8:47 A.M. TO 9:02 A.M. EDT

The burning of the jet fuel cloud had consumed much of the oxygen within the 94th and 96th floors, although photographs showing survivors indicated there were some zones with breathable air. The oxygen-starved fires died down, but didn't quite go out. Within the first 2 min after the impact, fires could be seen in the north side windows on the 93rd through 97th floors, the 96th floor of the south face, and the 94th floor of the east face. As fresh air entered the perforated facades, there began the steady burning of the office furnishings and the 13 tons of combustibles from the aircraft that would eventually overwhelm the already damaged building. By 9:00 a.m., these fires had grown and spread to the extent shown in Figure 2–5. In addition to burning around the aircraft entrance hole, there was intense burning on the north, east, and west faces of the 97th floor. Large fires burned on the south side of the 96th floor and the east side of the 94th floor. At 8:52 a.m., a stream of smoke emerged from the south side of the 104th floor, although there was no evidence of a significant fire there yet.

There was no way to fight the fires. The piping providing the water supply to the automatic sprinklers had been broken, and water was flowing down the stairwells. Even had this not happened, the system was designed to supply water to about 8 sprinkler heads at one time, enough to control the flames from as much as 1,500 ft^2 of burning material. The water supply was likely sufficient to control fires up to triple that size. The fires, however, had already grown far larger than that.



Note: Color coding—white, no fire; yellow, spot fire; red, fire visible inside; orange, external flaming.

Figure 2–5. Representation of exterior views of the fires on the four faces of WTC 1 from 8:47 a.m. to about 9:02 a.m.

There was also no way to abate the opaque, hot, and toxic smoke that quickly began accumulating. The manually activated smoke purging system was intended for smoke removal during fire department operations following a fire. Thus, it was not turned on during the 102 min that the tower would remain standing. It would not likely have helped anyway. Neither the World Trade Center Safety Director nor the arriving firefighters knew where the fires were located, so they could not have known how to direct the intake and exhaust flows. Furthermore, the integrity of the vent shafts on the upper floors had been compromised by the aircraft impact, making it unlikely that the system could have functioned as intended.

Most of the people in WTC 1 were aware of the possibility of an emergency. A quarter of them had been working in the building since before the 1993 bombing, and most of those had been in the building on that day. Half the people had been working in the building for at least two years; many had heard the stories and had participated in the emergency drills.

The building occupants knew that something serious had happened. A third of the survivors had heard the roar of the plane. Nearly two thirds reported feeling the violent movement of the building. Half sensed that they were in a life-threatening situation. At the Concourse Level, a fatal fireball filled the space from the elevators to the exit toward WTC 3. Almost immediately, people began calling 9-1-1, both for help and to find out more about what was going on.

Within 5 min to 8 min of the strike, most of the 7,545 people below the floors of impact began to evacuate. Their progress is tracked in Table 2–1. Water and debris were in the three stairwells. The air smelled of jet fuel and was becoming gray with smoke and pulverized gypsum, thermal insulation, and

concrete. Nonetheless, perhaps due to the guidance they had received since the 1993 bombing, for the most part the people moved in an orderly manner down the stairs, helping those who needed assistance. Within 15 min of the strike, nearly all of the people below the impact floors had descended about 10 floors from their original location.

Table 2–1. Locations of occupants of WTC 1.

Time	Evacuated	Lobby to 91st Floor	92nd to 110th Floor
8:46	0	7,545	1,355
9:03	1,250	6,300	1,355
9:59	6,700	850	1,355
10:28	7,450	107	1,355

Note: The numbers in the rows do not add to the estimated total of 8,900 due to rounding errors in the less certain values.

At the time, there were some survivors from the 92nd through 99th floors. Most of those who were able moved to the areas where the fires had not yet spread. Some were seen looking out from the former window spaces and even standing on the deformed structural steel. At 8:52 a.m., the first of at least 111 people was observed falling from the building.

Hundreds of people were on the floors above the impact zone. They soon realized that they were unable to go downward to get away from the smoke and heat that were building up around them. At 8:54 a.m., occupants began breaking windows to provide access to fresh air. By 9:02 a.m., 26 calls, representing hundreds of people, had been made to 9-1-1, asking for help and seeking more information about what was happening. Some of the people went toward the roof. However, there was no hope because roof evacuation was neither planned nor practical, and the exit doors to the roof were locked.

While the occupants were not advised in advance that roof evacuation was not a viable option, there was, and is, no requirement in the NYC Building Code for the roof to be accessible for emergency evacuation or rescue, and roof rescue was not contemplated in the WTC evacuation plans. Even had the roof been accessible, the helicopters could not have landed due to the severe heat and smoke.

Outside the building, a flurry of activity was beginning. Personnel of the Fire Department of the City of New York (FDNY) were several blocks away, investigating a gas leak at street level, and observed the aircraft impact. Within a minute, FDNY had notified its communications center and requested additional alarms for the WTC. A Port Authority Police Department (PAPD) unit had reported to its Police Desk that there had been an explosion with major injuries. By 8:50 a.m., the first fire engines had arrived, and an Incident Command Post had been established in the WTC 1 lobby. An Emergency Medical Service (EMS) Command was established 3 min later. More and more reports of damage, injuries, and deaths flooded the communications channels, and knowledge of the extent of the catastrophe was emerging. At 8:52 a.m., the first New York City Police Department (NYPD) aviation unit arrived to evaluate the possibility of roof rescue, but reported they were unable to land on the roof due to the heavy smoke. At 8:55 a.m., the firefighters entering WTC 1 began climbing the stairs (Figure 2–6). Their objectives were to evacuate and rescue everyone below the fires, then to cut paths through the fires and rescue all those above the fires.

At 8:59 a.m., a senior PAPD official called for evacuation of the entire WTC complex, although that call was not heard nor heeded by others. By 9:00 a.m., 66 FDNY units had been dispatched to the scene, and

Figure 2–6. Firefighters on the scene at about 9:07 a.m.

the FDNY had called a fifth alarm for the dispatch of additional department personnel and equipment to the WTC. Spectators had begun converging on the complex, but were advised to stand clear.

The aircraft impact also did damage to the communications in the tower. The capability for building-wide broadcast from the Fire Command Desk was knocked out. Emergency responder radio traffic peaked at about five times its normal traffic volume during the 20 min period after to the attack. This peak gradually tapered off, but still continued at a sustained level three times the normal traffic volume. The radio systems were not adequate to handle the high flow of emergency communications required for this scale of operations. Many of the radio messages were unintelligible because many individuals were trying to talk on the same radio channel at the same time.

2.6 9:02:59 A.M. EDT

At 9:02:59 a.m., five hijackers flew United Airlines Flight 175 with 9 crew and 51 passengers into the east side of the south face of WTC 2. For the most part, there was little awareness of this among the people below the 92nd floor of WTC 1. Almost one-fifth of these had already left the building, and nearly all the 6,300 others were already in the stairwells.

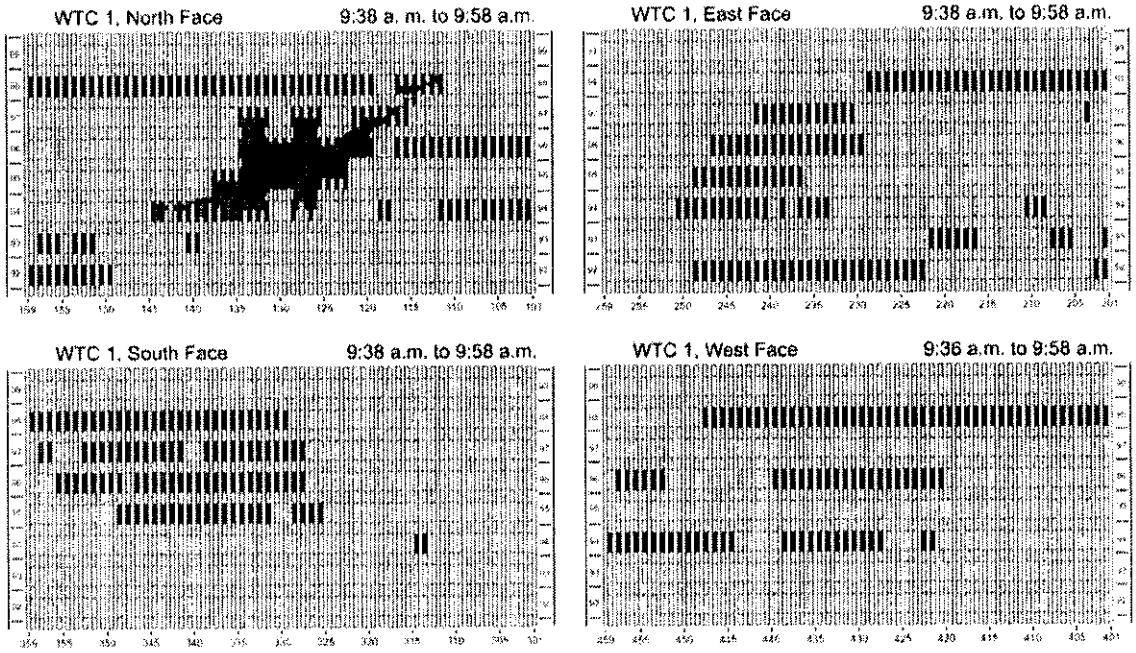
2.7 9:03 A.M. TO 9:57 A.M. EDT

A fire needs a continuing supply of both gaseous fuel and oxygen to keep burning, and the initially burning combustibles in WTC 1 were being consumed. The additional fuel came from the office furnishings next to those that were reaching the end of their burning life. The thermal radiation from the flames and from the hot gases heated the nearby combustibles, creating flammable vapors. These vapors needed a source of nearby air to continue the burning. The same flames and hot ceiling layer gases heated the windows and window frames in the vicinity. The hot gases pushed on the weakened aluminum

frames, sending some windows outward to fall to the Plaza below. Other windows were sucked into the building. The fires now had both new fuel and fresh air.

And so the fires continued to spread, likely aided by as-yet unburned jet fuel that had soaked into some of the furnishings and flooring. The coating of (non-combustible) gypsum and concrete fragments slowed the burning rate by as much as half, but could not halt the fire from spreading. The overall movement of the fires was toward the south side of the tower. By 9:15 a.m., the fires on the 97th floor had intensified and filled most of the floor. Large fires had erupted on the east sides of the 92nd and 96th floors.

Seventy-five minutes after the impact, approaching 10:00 a.m., the fire on the 97th floor had begun to burn itself out, but the fire on the 94th floor had intensified and filled much of the north half of the floor (Figure 2–7). Starting about 9:30 a.m., there were vigorous fires on nearly the full perimeter of the 98th floor. There was still almost no burning on the 99th floor or above.



Note: Color coding—white, no fire; yellow, spot fire; red, fire visible inside; orange, external flaming.

Figure 2–7. Representation of exterior views of the fires on the four faces of WTC 1 from about 9:38 a.m. to 9:58 a.m.

The hot smoke from the fires now filled nearly all the upper part of the tenant space on the impact floors. Aside from isolated areas, perhaps protected by surviving gypsum walls, the cooler parts of this upper layer were at about 500 °C, and in the vicinity of the active fires, the upper layer air temperatures reached 1,000 °C. The aircraft fragments had broken through the core walls on the 94th through the 97th floors, and temperatures in the upper layers there were similar to those in the tenant spaces.

The perimeter columns, floors, and core columns were immersed in these hot gases and began to weaken. Where the insulation was dislodged, the temperature of the steel rose rapidly, in contrast to steel members where insulation was intact (Figure 2–8). The heaviest core columns with damaged insulation heated slowly, as the absorbed heat was dissipated through their massive cross sections. The temperatures of the lighter columns and the floor slabs rose more quickly, and those of the stripped trusses even more so.

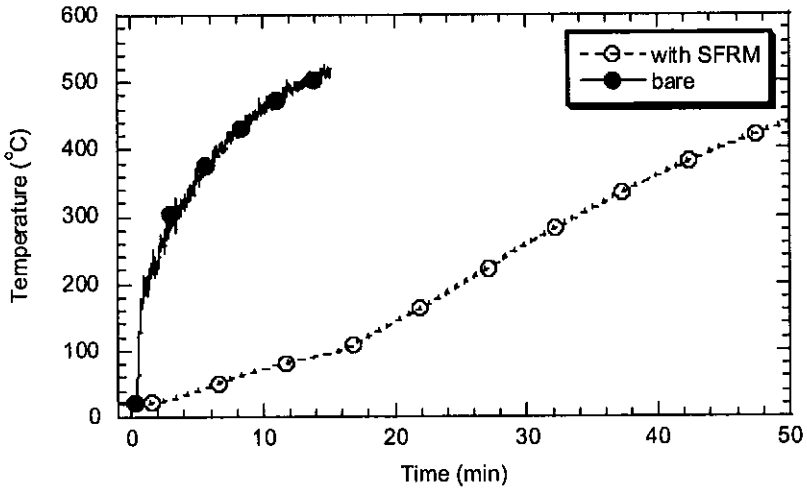


Figure 2–8. Steel surface temperatures on the bottom chords of fire-exposed trusses, uninsulated and insulated with ¾ in. of BLAZE-SHIELD DC/F.

As a steel column is heated, its ability to support gravity loads and resist lateral loads decreases. At temperatures of about 300 °C, steel loses about 20 percent of its yield strength (Figure 2–9). Under modest loads, steel is *elastic*, that is, it can compress, or shorten, but will recover when loads are removed. As the load increases, the steel becomes *plastic*, and the shortening is unrecoverable. At still higher loads, the column buckles. At temperatures above 500 °C, the steel further weakens, the loss of strength and stiffness become significant, and the column's ability to carry its share of the building loads decreases. It shortens due to a combination of plastic deformation and an additional, time-dependent deformation called *creep* that can increase column shortening and hasten buckling. Figure 2–10 indicates the rates at which structural steel could have been heated by the WTC fires and the effect of the thermal insulation in slowing the heating process.[6]

Structural steels do not need to melt to lose strength. Their melting points are about 1,600 °C, well above the 1,100 °C typical peak value reached by fires of common building combustibles.

At this point, the core of WTC 1 could be imagined to be in three sections. There was a bottom section below the impact floors that could be thought of as a strong, rigid box, structurally undamaged and at almost normal temperature. There was a top section above the impact and fire floors that was also a heavy, rigid box. In the middle was the third section, partially damaged by the aircraft and weakened by heat from the fires. The core of the top section tried to move downward, but was held up by the hat truss. The hat truss, in turn redistributed the load to the perimeter columns.

[6] Chapter 6 contains an explanation of how these temperature profiles were developed.

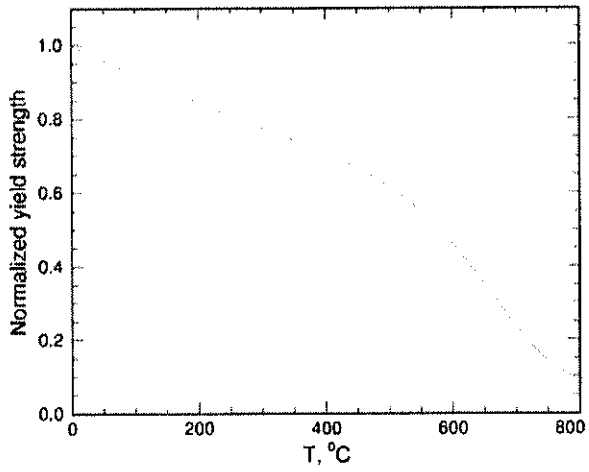
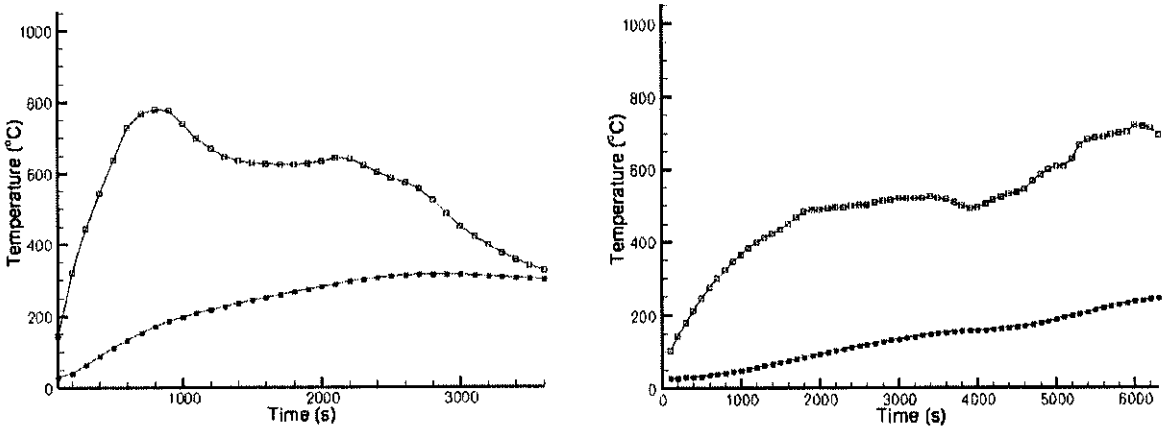


Figure 2–9. Temperature dependence of yield strength of structural steel as a fraction of the value at room temperature.



Note: The red data are for structural steel components without insulation; the blue data are for steel components that are still insulated.

Figure 2–10. Simulated temperatures of two adjacent trusses (left) and two adjacent perimeter columns (right) exposed to the fires in WTC 1.

Simultaneously, the fires were creating another problem for the tower. The floors of the 93rd through the 97th stories were being heated both by the hot gases from below and by thermal radiation from the fires on the floor above (Figure 2–11). On the south side of the building, where the fires were heating the long-span trusses whose SFRM had been dislodged, the floors began to sag. In so doing, they began pulling inward on their connections to the south face and to the core columns. Pull-in forces due to the sagging floors did not fail the floor connections in most areas.

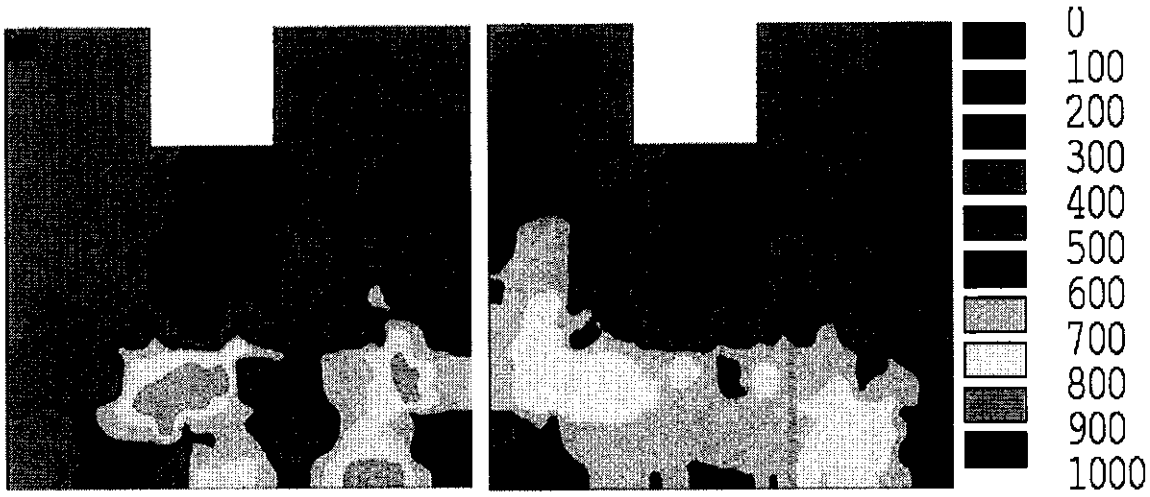


Figure 2–11. Temperature contours (°C) on the top and bottom faces of the concrete slab (96th floor, WTC 1) at 100 min after impact. A portion of the concrete slab on the north face (top) was damaged by the impact of the aircraft.

Meanwhile, the occupants from below the impact floors were moving steadily down the stairs at roughly a floor per minute. Although they encountered firefighters climbing upward, this did not slow the downward progress much. Within 75 min of the impact, 90 percent of the people who would survive had left WTC 1. At 9:37 a.m., a Port Authority official instructed all units to direct the evacuees over the bridge on West Street to the Financial Center. However, this change in evacuation route actually began with the collapse of WTC 2.

Conditions on floors 92 and above continued to deteriorate. The presence of the fires and the resulting high smoke and radiant heat levels made the 92nd floor through the 99th floor uninhabitable except in small areas. Above the impact zone, there were only seven calls to 9-1-1 between 9:03 a.m. and 9:10 a.m.; and then, more than a half hour later, three last calls from floors 104 and 105 between 9:43 a.m. and 9:57 a.m. More people jumped through windows they broke or that had been broken by the fires.

By 9:15 a.m., 30 FDNY units had signaled their arrival, and by 9:59 a.m., the number had grown to 74. They had been told to stop short of the site because of the large number of ambulances already there and the debris falling from the buildings. Many of the firefighters proceeded into WTC 1. Once inside, they found that only one of the 99 upward elevators was working, one that went as far as the 16th floor. Most of the firefighters then proceeded to ascend the three stairways, intending to help evacuate the occupants, cutting paths through the fires as necessary. Because the firefighters were carrying as much as a hundred pounds of bulky firefighting gear, their progress was slow and was impeded by the flow of evacuees coming down the stairs. A few reached as high as floors in the 40s and 50s.

Since the Command Boards were destroyed in the collapse, it is unknown just how many firefighters went into WTC 1, when they went in, or, in most cases, what level they reached.

2.8 9:58:59 A.M. EDT

With no warning that could be discerned in WTC 1, WTC 2 collapsed. The shudder as the more than 250,000 tons of steel, concrete, and furnishings hit the ground was felt well beyond the site. Seismic sensors located 100 miles away recorded the time and intensity of the event.

The gigantic concussion was felt by some of the nearly 800 people still in the stairwells in WTC 1. The evacuation rate slowed to half its prior level as a new cloud of dust, smoke, and debris filled the Concourse and the stairwells, and the lights went out. Higher up, no more calls to 9-1-1 originated from above the 91st floor.

At 10 a.m., NYPD and FDNY ordered all emergency responders out of WTC 1 and away from the WTC site.

2.9 9:59 A.M. TO 10:28 A.M. EDT

For the next half hour, the last 690 of the eventual survivors worked their way down the last flights of stairs, across West Street to the west and across Vesey Street to the north and to safety. By 10:28 a.m., all but 107 of the roughly 7,500 people who had been below the impact floors were able to escape.

At 10:06 a.m., an NYPD aviation unit advised that WTC 1 would come down and that all emergency vehicles should be moved away from it. At 10:20 a.m., observers in NYPD helicopters said that the top of the building was leaning; and at 10:21 a.m., they said that WTC 1 was buckling on the southwest corner and leaning to the south.

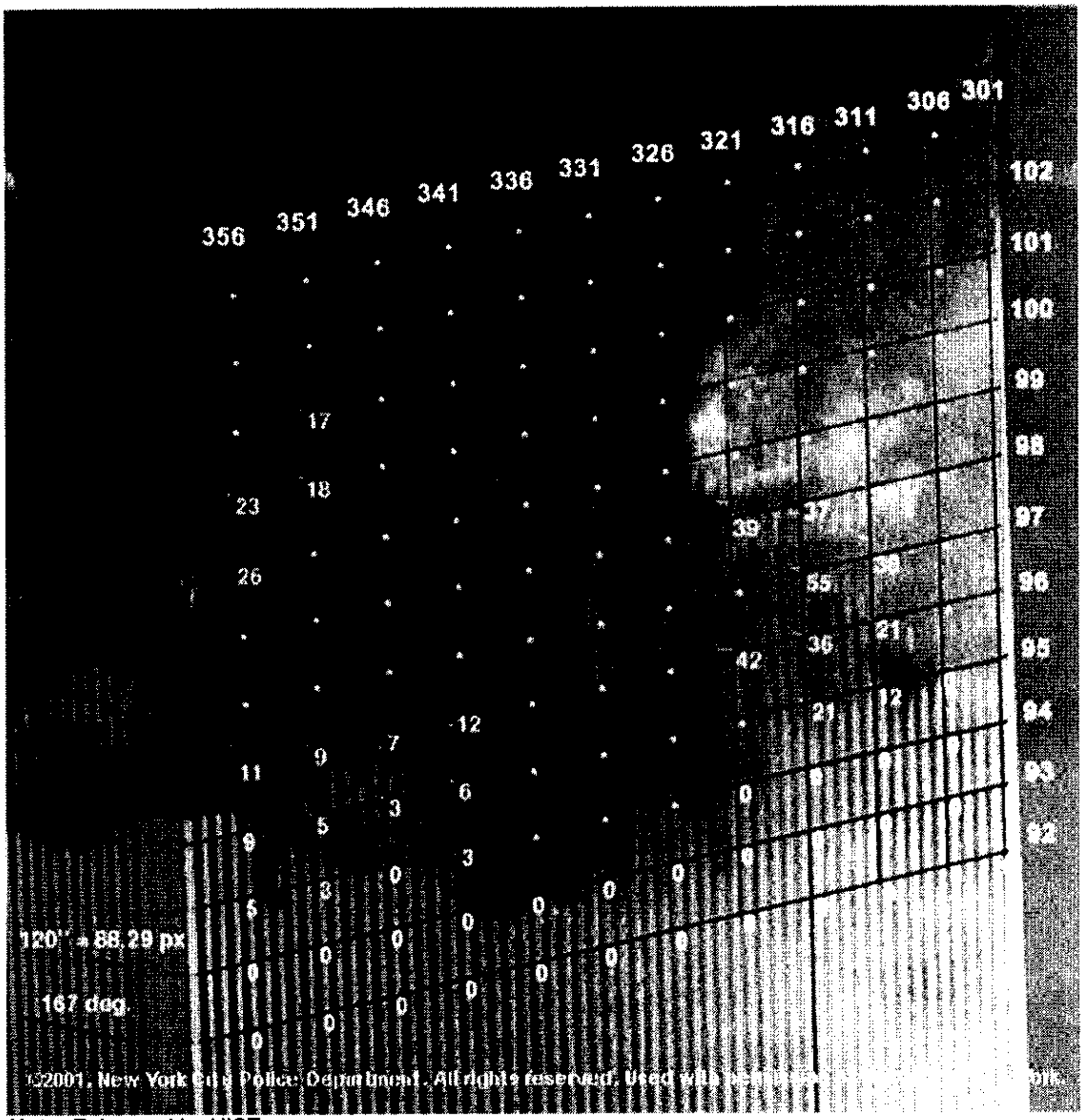
Having heard over their radios the orders that they should evacuate, some of the responders inside the tower headed down the stairwells and out of the building, telling their comrades on the way. Others did not, having not received the message, having climbed too high to now get out in time, or continuing on the missions to help others still in the building.

A pressure pulse generated by the collapse of WTC 2 appeared to intensify the fires in WTC 1. Within 4 s of the collapse of WTC 2, flames burst from the south side windows of the 98th floor. The fires on the north faces of the 92nd, 94th, and 96th floors brightened noticeably. Flames near the south end of the east face of the 92nd and 96th floors also flared. The fires on the east and south faces of the 98th floor already extended out the windows. Those in the WTC 1 stairwells felt a gush of wind.

At 10:01 a.m., flames began coming out of the south side of the west face of the 104th floor, three floors higher than any floor where fire had been previously observed and five floors above the highest floor with a major fire. After a rapid growth period, this fire burned intensely up to the time the tower collapsed.

By 10:18 a.m., a substantial pressure pulse inside the building ejected jets of smoke from the 92nd and 94th through 98th floors of the north faces and the 94th and 98th floors of the west face. Fires raged on the south side of the 96th through 99th floors.

The sagging of the floors had increased. Although the floors on the north side of the tower had sagged first, they contracted due to cooling when the fires moved toward the south. Now, the south side floors had sagged to the point where the south perimeter columns bowed inward (Figure 2–12). By 10:23 a.m., the south exterior wall had bowed inward as much as 55 in.



Note: Enhanced by NIST.

Figure 2–12. South face of WTC 1 at 10:23 a.m., showing inward buckling (in inches) of perimeter columns.

The tower was being overwhelmed. Three of the four major structural systems—the core, the floors, and the perimeter walls—were weakening. The south wall became unstable and tried to transfer its remaining load to the weakened core via the hat truss and to adjacent perimeter columns via the spandrels. The entire section of the building above the impact zone began tilting as a rigid block toward the south. The upper section of the building then collapsed onto the floors below. Within 12 s, the collapse of WTC 1 had left nothing but rubble.

2.10 THE OUTCOME

Seven major factors led to the collapse of WTC 1:

- Structural damage from the aircraft impact;
- Large amount of jet fuel sprayed into the building interior, that ignited widespread fires over several floors;
- Dislodging of SFRM from structural members due to the aircraft impact, that enabled rapid heating of the unprotected structural steel;
- Open paths for fire spread resulting from the open plan of the impact floors and the breaking of partition walls by the impact debris;
- Weakened core columns that increased the load on the perimeter walls;
- Sagging of the south floors, that led to pull-in forces on the perimeter columns; and
- Bowed south perimeter columns that had a reduced capacity to carry loads.

After the building withstood the initial aircraft damage, the timing of the collapse was largely determined by the time it took for the fires to weaken the core and to reach the south side of the building and weaken the columns and floor assemblies there.

There were no survivors among the 1,355 people who were on or above the 92nd floor. The aircraft had destroyed all egress paths downward, and roof rescue was impossible.

Of the roughly 7,545 building occupants who started that morning below the 92nd floor, all but 107 escaped the building. Those left behind were trapped by debris, awaiting assistance, helping others, or were just too late in starting their egress. For the most part, the evacuation was steady and orderly.

Had the building been significantly more than one-third to one-half occupied, the casualties would likely have been far higher, since the exiting population would have exceeded the capacity of the stairwells to evacuate them in the time available.

Six percent (almost 500) of the survivors from WTC 1 had a limitation that impaired their ability to evacuate. Many of these were able to evacuate, often with assistance; others were less fortunate. About 40 to 60 mobility-impaired occupants were found on the 12th floor, where they had been placed in an attempt to clear the stairways. Just before the collapse of WTC 1, emergency responders were assisting about 20 of these people down the stairwell. It remains unclear how many of these people survived.

Those emergency responders who entered the building and the emergency personnel who were already in the building were helpful in assisting the evacuation of those below the impact floors. However, there was insufficient time and no path to reach any survivors on the impact floors and above. Any attempts to mitigate the fires would have been fruitless due to the lack of water supply and the difficulty in reaching the fire floors within the time interval before the building collapse. It is not known precisely how many

emergency responders entered the building nor how many of the 421 responder casualties occurred in WTC 1. NIST estimated that approximately 160 FDNY fatalities occurred outside the WTC towers.

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